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A RADIATIVE TRANSFER MODEL FOR MICROWAVE EMISSION FROM SOILS

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ABSTRACT

The radiative transfer equation for an absorbing medium is used to develop a model for microwave emission from soils. The model calculates the microwave emission intensity in terms of the brightness temperature as a function of the soil moisture and temperature. The consistency of the model is verified by a comparative study of the present model with other microwave emission models. The effect of surface roughness on the brightness temperature is studied by modifying the Fresnel reflection coefficient and by including the surface depolarization effect. The quantitative effect of the surface roughness is studied and it is demonstrated that the brightness temperatures observed for a natural agricultural terrain can be explained through the inclusion of the roughness effect. The surface roughness effect is further analyzed to obtain formulae which are useful in the analysis of the brightness temperatures, particularly, to obtain soil moisture information from the brightness temperatures. The sensitivity of the brightness temperature to the soil temperature variations is studied both qualitatively and quantitatively. A simple formula is obtained to calculate the soil temperature dependence of the brightness temperature in terms of the surface and the deep soil temperatures. An algorithm to normalize the brightness temperatures so as to compare microwave observations under different soil temperature conditions is also discussed. A program listing of the model is given in the appendix.

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SECTION 1 - INTRODUCTION

One of the most promising techniques for the remote sensing of soil moisture is the use of passive microwave sensors. The microwave frequencies are chosen because at these frequencies there is a large difference in the dielectric properties of water and dry soils. Since the emitted energy originates at different depths within the volume of the soil, the analysis of the emitted microwave energy is expected to provide the subsurface soil moisture information.

The purpose of this memorandom is to present a theoretical model for microwave emission from bare agricultural soils. The model utilizes the radiative transfer equation to calculate the emitted energy in terms of brightness temperature for a specified polarization state as a function of the moisture and the temperature within the soil. The predictions of the model are compared with other microwave emission models - the Burke-Paris model (Reference 1) and the Wilheit model (Reference 2). A quantitative study has been performed to show the effect of surface roughness on the emitted microwave energy. The effect of diurnal variation of soil temperature on the brightness temperature has also been studied.

The model is formulated in Section 2, Section 3 contains the comparative study of the model, in Sections 4 and 5 the effect of surface roughness are studied and in Section 6 the diurnal variation of the brightness temperature is discussed. A listing of the computer program is given in the appendix.

SECTION 2 - MICROWAVE EMISSION MODEL

In this section we will formulate a model for calculating the intensity of microwave emission from a bare agricultural soil. In developing this model the following simplifying assumptions will be made:

1. The radiation is incoherent.
2. Moisture and temperature within the soil are functions of depth only.
3. Internal reflection of the emerging radiation due to the gradient in the moisture profile is negligible.

To describe the volumetric emission of the radiation from the soil we will use the radiative transfer equation.

The general form of this equation is:

$$-\frac{dI}{dz} = -\gamma_e(z)\, I + S(z)\ , \qquad 0 \le z \le \infty \tag{2-1}$$

where z is the depth into the soil, I is the instensity of the radiation in the upward direction at depth z, $\gamma_e(z)$ is the extinction per unit length, and $S(z)$ is the source function of the radiation which involves the scattering and the internal thermal emission within the soil. The coordinate z is decreasing towards the soil surface.

Since soil is a highly opaque medium, one can neglect the effect of scattering on the emerging radiation. Also, at microwave frequencies, one can use the Rayleigh-Jeans approximation, to replace the internal thermal emission by a term which is directly proportional to the temperature within the soil, $T(z)$.

The general radiative transfer Equation (2-1) then reduces to the equation (Reference 1):

$$-\frac{dt}{dz} = -\gamma_a(z)\, t + \gamma_a(z)\, T(z) \tag{2-2}$$

where t is the radiation intensity expressed in units of temperature, $\gamma_a(z)$ is the absorption coefficient of the soil, and $T(z)$ is the soil temperature.

By integrating (Equation (2-2)) over the soil depth, one can calculate the total microwave intensity in units of temperature as:

$$t = \int_0^\infty T(z)\gamma_a(z)\, \exp\left(-\int_0^z \gamma_a(z')\, dz'\right) dz \tag{2-3}$$

The integrated microwave intensity in Equation (2-3) can be interpreted as the effective soil temperature. One can easily verify that if the temperature within the soil is constant then the integrated microwave intensity (Equation (2-3)) is equal to the soil temperature.

The intensity of the radiation emerging from the soil, called the brightness temperature, can be calculated using geometrical optics as:

$$T_{Bp} = (1 - r_p)\, t \tag{2-4}$$

where r_p is the reflectivity of the soil surface for the polarization state, p.

In the following we will discuss the calculation of the absorption coefficient, $\gamma_a(z)$, and the reflectivity, r_p, using the soil moisture information. These quantities, however are not directly related to the soil moisture but to the dielectric constant of the soil.

Using the theory of electromagnetic waves in a lossy dielectric medium, one can obtain the absorption coefficient as the damping factor for the intensity of the radiation as (Reference 3, Chapter XIII and Reference 1):

$$\gamma_a(z) = \frac{4\pi}{\lambda}\alpha(z, \theta_o) \tag{2-5}$$

where λ is the wavelength of the radiation, θ_o is the angle of observation measured with respect to the stratification, and

$$\alpha(z, \theta_o) = \frac{\epsilon_2(z)}{2\beta(z, \theta_o)} \tag{2-6}$$

$$\beta(z, \theta) = \left[\frac{1}{2}\left\{\epsilon_1(z) - \sin^2\theta_o\right\}\cdot\left\{\left(1 + \frac{\epsilon_2^2(z)}{(\epsilon_1(z) - \sin^2\theta_o)^2}\right)^{1/2}\right\}\right]^{1/2} \tag{2-7}$$

where ϵ_1 and ϵ_2 are respectively the real and the imaginary parts of dielectric constant, $\epsilon(z)$, at depth, z:

$$\epsilon(z) = \epsilon_1(z) + i\,\epsilon_2(z) \tag{2-8}$$

For a smooth soil surface the reflectivity r_p can be calculated from the Fresnel equation, where the result for the horizontal polarization is

$$r_p = \left|\frac{k - \cos\theta_o}{k + \cos\theta_o}\right|^2 \tag{2-9}$$

and for the vertical polarization the result is

$$r_p = \left| \frac{k - \epsilon(o) \cos\theta_o}{k + \epsilon(o) \cos\theta_o} \right|^2 \qquad (2-10)$$

Here, $\epsilon(o)$ is the diectric constant at the soil surface and k is a complex number defined as:

$$k = \beta\,(z = 0, \theta_o) + i\,\alpha\,(z = 0, \theta_o) \qquad (2-11)$$

The Equations (2-3) through (2-11) constitute the basis of the model. Numerical evaluation of these equations requires the knowledge of the temperature, $T(z)$, and the dielectric constant, $\epsilon(z)$, within the soil. For the calculation of the dielectric constant, one requires the soil moisture information (Reference 4). Thus the main input parameters of the model are the soil moisture and the soil temperature as a function of depth. It is to be noted that the contribution of the sky radiation to the observed microwave emission intensity has been neglected in Equation (2-4). This contribution can easily be included by adding the term $(r_p T_{sky})$ in Equation (2-4), where T_{sky} is the sky radiation intensity in units of temperature.

In the next section we will compare the predictions of the present model with other microwave emission models.

SECTION 3 - COMPARATIVE STUDY OF THE MODEL

The model developed in the previous section was based upon some simplifying assumptions. Since, a priori, it is not possible to assess the quantitative error involved with these assumptions, we will make a comparative study of the present model with other microwave emission models.

The microwave emission model developed by Burke and Paris (Reference 1) has some resemblance with the present model. The main difference between them is in the method of integrating the radiative transfer Equation (2-2). In the Burke-Paris model, the soil medium is divided into layers of constant soil moisture. Based upon experimental data, the minimum thickness of the layer was chosen to be one centimeter. The radiation intensity within each layer was calculated by integrating the radiative transfer equation. In calculating the total intensity, the effect of discontinuity in the dielectric constant at the interface of two consecutive layers, was incorporated through the reflection and the transmission of intensity at the interfaces. Because we have neglected the aforementioned dielectric discontinuity effect, the present model is a limiting case of the Burke-Paris model for negligible internal reflection of the radiation.

The model developed by Wilheit (Reference 2) is based upon the theory of electromagnetic waves in a layered dielectric. After calculating the amplitudes of the electric and the magnetic fields within each layer, the fraction of energy absorbed within the layer was obtained by applying Poynting's theorem. The total intensity of the emerging radiation was calculated by weighting the soil temperature of each layer with the fraction of the energy absorbed within that layer. Since the fundamental quantity in the Wilheit's model is the amplitude of the electromagnetic field, the microwave radiation within the soil has been treated as a coherent radiation. In the present model we have assumed that the radiation is incoherent within the soil.

To determine the quantitative difference between different models, we calculated the brightness temperature using the soil moisture and temperature profiles measured by Jackson (Reference 4). These soil profiles are representative of the profiles observed under varied soil conditions. The dielectric constant was calculated from the soil moisture using the linear regression results given in Reference 4. The calculated brightness temperatures at the nadir observation are given in the Table 3-1 for 1.55 cm wavelength radiation and in the Table 3-2 for 21 cm wavelength radiation. In these tables we have also specified the average soil moisture associated with these profiles. The results for the Wilheit model are taken from Reference 4. A listing of the computer program, used in this calculation, is given in the appendix.

The results in Tables 3-1 and 3-2 show that for both wavelengths, the agreement between the present model and the Burke-Paris model is quite good. This agreement indicates that one can neglect internal reflections due to the dielectric discontinuity at the layer interfaces.

At small wavelength, the results of the present model agree with the Wilheit model. At longer wavelength (21 cm radiation) however the results of present model are higher than those of the Wilheit model. This disagreement is particularly noticeable for intermediate moisture profiles (i.e., the profiles 3, 4, and 5). We have already stated the difference in the formulation of two models. Whether or not the radiation within the soil is coherent remains to be investigated. It is also not clear why the two models should show such a large disagreement for intermediate moisture profiles only. By comparing the observed brightness temperatures with the model calculations, we will illustrate in the next section, that this difference between the two models can not be resolved conclusively.

Table 3-1. Brightness Temperature for 1.55 cm Radiation at Nadir Observation

Profile	Present Model	Burke-Paris	Wilheit	Soil Moisture (unit: Weight percent) 0-1 cm	Soil Moisture (unit: Weight percent) 0-2.5 cm
1	191.0	191.2	195.6	20.9	20.3
2	212.6	212.9	217.1	16.1	16.5
3	272.0	271.6	275.5	11.0	13.8
4	279.9	279.2	281.2	8.4	12.0
5	285.0	284.4	286.8	5.6	9.9
6	284.7	284.3	287.0	4.4	8.3
7	287.5	287.2	288.7	3.0	5.7
8	290.4	290.4	291.1	2.3	3.8
9	295.7	295.7	296.3	1.7	2.4

Table 3-2. Brightness Temperatures for 21.0 cm Radiation at Nadir Observation

Profile	Present Model	Burke-Paris	Wilheit	Soil Moisture (unit: Weight percent) 0-1 cm	Soil Moisture (unit: Weight percent) 0-2.5 cm
1	177.3	177.5	173.2	20.9	20.3
2	203.9	204.1	202.7	16.1	16.5
3	250.7	249.2	229.4	11.0	13.8
4	262.0	260.4	242.1	8.4	12.0
5	270.3	269.0	258.4	5.6	9.9
6	271.6	270.5	268.3	4.4	8.3
7	273.6	272.6	273.0	3.0	5.7
8	273.9	272.9	276.1	2.3	3.8
9	278.9	278.0	279.1	1.7	2.4

SECTION 4 - SURFACE ROUGHNESS EFFECT

The comparative study presented in the previous section show that the results of the present model are in good agreement with other microwave emission models, at least in the extreme cases of the soil moisture. However, when the results of this model were compared with the observed brightness temperatures (Reference 4) unexplainable discrepancies were observed, especially for wet soil cases. Although there was a considerable amount of scatter in the observed data, it can be conclusively noted that the observed brightness temperatures were significantly higher than the model calculation. Since the surface of a natural agricultural terrain, for which the brightness temperatures were observed, is not a smooth surface, we need to study the effect of surface roughness on the microwave brightness temperature. The purpose of this section is to outline a model which shows the effect of surface roughness on the brightness temperatures. We will also show that the roughness model developed in this section can provide an explanation of the observed brightness temperatures.

The geometry of the soil surface enters in our model in Equation (2-4) where we evaluate the emergent radiation. If the surface is smooth, the emergent radiation can be evaluated using the Fresnel formula given by Equations (2-9) and (2-10). For rough surfaces, these Fresnel formulae are not valid. We will now discuss the effect of surface roughness on physical and mathematical grounds.

From geometrical optics (Reference 3) the radiation incident at any point on the surface will propagate in the direction which is determined by the angle of the incident radiation with respect to the normal at that point. For a smooth surface, the direction of the normal is the same at all points on the surface and the incident radiation gets reflected or transmitted along a unique direction at all points on the surface. The direction of normal at any point on the rough surface depends upon the location of that point, so the incident radiation will be reflected or transmitted along many directions and the energy transmitted along any particular direction (the observed brightness temperature) will be modified by the surface geometry.

The polarization state of radiation is defined with respect to a coordinate system which consists of the tangent and the normal to the surface at the point of incidence. For a smooth surface, since a coordinate system can be specified uniquely, the energy transmitted in any polarization state is also unique. For a rough surface, only the local coordinate system is unique for any given point on the surface. To define and measure the energy in any polarization state, when the surface is rough, one requires a standard coordinate system. This standard coordinate system generally consists of the mean normal and the mean tangent on the surface. It is thus expected that when the energy measured in any polarization which has been defined with respect to a standard coordinate system, then that energy should actually be a mixture of energies transmitted in both polarization states.

The above effects of roughness will now be stated mathematically. If the rough surface has a statistical height distribution, then the effect of surface roughness is essentially to modify the Fresnel reflectivity by an exponential factor of the form (References 5 and 6):

$$\exp\left(-h \cos^2 \theta_0\right) \tag{4-1}$$

where θ_0 is the angle of observation and h is a parameter which specifies the roughness height.

This modification of the Fresnel reflectivity accounts for the radiation energy being reflected along many directions. We have also noted that the energy in any polarization state should actually be represented by a mixture of energies in both polarization states. If Q is the mixing coefficient for the polarization states, then the appropriate reflectivites which should be used in Equation (2-4) are the following; for the horizontal polarization:

$$\tilde{r}_H(\theta_0) = [(1 - Q)\, r_H(\theta_0) + Q\, r_V(\theta_0)] \exp\left(-h \cos^2\theta_0\right) \tag{4-2}$$

for the vertical polarization:

$$\tilde{r}_V(\theta_0) = [(1 - Q)\, r_V(\theta_0) + Q\, r_H(\theta)] \exp\left(-h \cos^2\theta_0\right) \; . \tag{4-3}$$

where $r_H(\theta_0)$ and $r_V(\theta_0)$ are, respectively, the Fresnel reflectivities for the horizontal and the vertical polarization states (Equations (2-9) and (2-10)).

The Equations (4-2) and (4-3) are the main formulae of the roughness model. These formulae have been stated based on the analysis of the effect of surface roughness on the emergent radiation. To verify the quantitative accuracy of the roughness model (i.e., the use of Equations (4-2) and (4-3) in Equation (2-4)), we recalculated the brightness temperatures for the soil moisture and temperature profiles given in Table 3-2. They are shown in Figure 4-1, together with the observed values (Reference 4). This figure shows that the roughness model presented here is capable of providing a quantitative explanation of the observed brightness temperatures. It should be noted that for the nadir observation, which we have plotted in this figure, the brightness temperatures are independent of the mixing coefficient, Q (see Equations (4-2) and (4-3) for $\theta_0 = 0$) .

The roughness model developed in this section contains two undetermined parameters, namely, h and Q . In the next we will discuss these parameters and also derive relations which will be useful in the analysis of brightness temperatures.

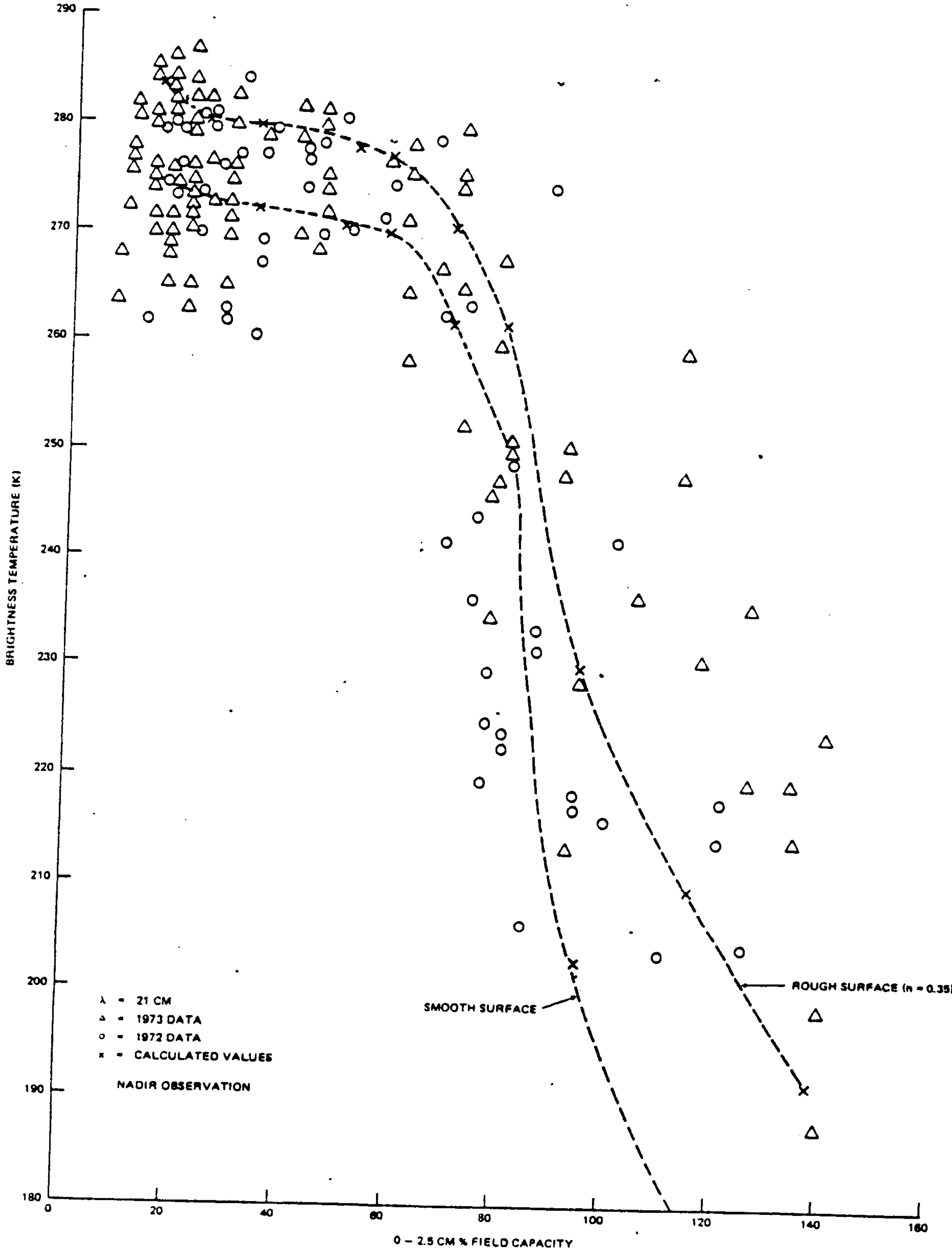

Figure 4-1. Comparison of Observed and Calculated Brightness Temperatures for Nadir Observation; 21 cm Radiation

SECTION 5 - ANALYSIS OF THE ROUGHNESS MODEL

The brightness temperatures observed for a natural agricultural terrain are expected to be affected by the surface roughness. In this section we will use the previous section to derive some formulae which can be useful in the analysis of the observed brightness temperatures.

From Equations (2-4), (4-2), and (4-3), the nadir and the off-nadir brightness temperatures can be explicitly written as:

$$T_B(o) = [1 - \tilde{r}(o)\, e^{-h}]\, t(\theta_o = 0) \tag{5-1}$$

$$T_{BH}(\theta_o) = [1 - \tilde{r}_H(\theta_o)]\, t(\theta_o) \tag{5-2}$$

$$T_{BV}(\theta_o) = [1 - \tilde{r}_V(\theta_o)]\, t(\theta_o) \tag{5-3}$$

The angular variation of the effective temperature, $\bar{t}$, is small when the angle of observation is not too far from the nadir. By neglecting this angular variation, one can define the normalized brightness temperatures to be the ratio of the brightness temperature and the effective temperature, as:

$$T_{NB}(o) = 1 - r(o)\, e^{-h} \tag{5-4}$$

$$T_{NBH}(\theta_o) = 1 - \tilde{r}_H(\theta_o) \tag{5-5}$$

$$T_{NBV}(\theta_o) = 1 - \tilde{r}_V(\theta_o) \tag{5-6}$$

It will be discussed in the next section that these normalized brightness temperatures are useful in comparing the brightness temperatures observed under varied soil temperature conditions.

From Equations (4-2) and (4-3) we can write

$$\tilde{r}_H(\theta_o) + \tilde{r}_V(\theta_o) = [r_H(\theta_o) + r_V(\theta_o)] \exp(-h \cos^2\theta_o) \tag{5-7}$$

$$\tilde{r}_H(\theta_o) - \tilde{r}_V(\theta_o) = [r_H(\theta_o) - r_V(\theta_o)] (1 - 2Q) \cdot \exp(-h \cos^2\theta_o) \tag{5-8}$$

Using Equation (5-4) we can write

$$\exp(-h \cos^2\theta_o) = \left[\frac{1 - T_{NB}(o)}{r(o)}\right]^{\cos^2\theta_o} \tag{5-9}$$

If we now combine the Equations (5-5, (5-6), (5-7), and (5-9) then the following relation between the nadir and the off-nadir brightness temperatures can be obtained:

$$\frac{1 - \left[\frac{T_{NBH}(\theta_o) + T_{NBV}(\theta_o)}{2}\right]}{\left[1 - T_{NB}(o)\right]^{\cos^2\theta_o}} = \frac{1}{2}\left[\frac{r_H(\theta_o) + r_V(\theta_o)}{\left[r(o)\right]^{\cos^2\theta_o}}\right] \tag{5-10}$$

The left hand side of Equation (5-10) contains the brightness temperatures for an arbitrary rough surface but the right hand side contains the reflectivities of a smooth surface. The equality of two quantities imply that the following brightness temperature parameter,

$$B = \frac{1 - \left[\frac{T_{NBH}(\theta_o) + T_{NBV}(\theta_o)}{2}\right]}{\left[1 - T_{NB}(o)\right]^{\cos^2\theta_o}} \tag{5-11}$$

must be independent of all effects of the surface roughness. Thus, for a given soil, if the moisture dependence of B is known then that moisture dependence should remain the same for all surface roughness conditions. We have thus identified a brightness temperature quantity which is independent of all surface roughness effects.

From the above equations one can also derive the following relation among the off-nadir brightness temperatures only:

$$\frac{1 - \left[\dfrac{T_{NBH}(\theta_o) + T_{NBV}(\theta_o)}{2}\right]}{T_{NBV}(\theta_o) - T_{NBH}(\theta_o)} = \frac{1}{2}\left[\frac{r_H(\theta_o) + r_V(\theta_o)}{\{r_H(\theta_o) - r_V(\theta_o)\}\,(1 - 2Q)}\right] \tag{5-12}$$

Since the only roughness parameter which appears in Equation (5-12) is the mixing parameter, Q , one should be able to identify this parameter by comparing the brightness temperature quantity appearing in the left hand side of Equation (5-12) with the corresponding quantity for a smooth surface. One should also note that the brightness temperature quantity appearing in the left hand side should increase with the increase in roughness.

From Equation (5-4) one can derive a relation between the smooth surface brightness temperature, $T^S_{NB}(o)$ and the rough surface brightness temperature, $T^S_{NB}(o)$, observed under similar moisture conditions as:

$$\left[1 - T^R_{NB}(o)\right]e^h = \left[1 - T^S_{NB}(o)\right] \tag{5-13}$$

Since the only roughness parameter appearing in Equation (5-13) is the parameter, h , one should be able to use Equation (5-13) to identify this parameter from the observed brightness temperatures. From Figure 4-1 we see that for drier soils, the brightness temperatures under both smooth and rough surface conditions, are less sensitive to the soil moisture. Thus, under dry soil conditions, one can use Equation (5-13) to determine the roughness parameter without knowing the exact value of the soil moisture. If the roughness parameter is known, then Equation (5-13) is expected to be useful in estimating the soil moisture from the observed brightness temperatures and known moisture dependence of the brightness temperature for a smooth surface. Thus, the relation Equation (5-13) should be useful for a statistical inversion purpose.

It should be noted that for off-nadir observations one can use Equations (5-5), (5-6) and (5-7) to obtain

$$1 - \frac{1}{2}[T_{NBH}(\theta_o) + T_{NBV}(\theta_o)] = \frac{1}{2}[r_H(\theta_o) + r_V(\theta_o)] \exp(-h \cos^2 \theta_o) \qquad (5\text{-}14)$$

In analogy with Equation (5-12) we see that the brightness temperature quantity appearing on the left hand side of Equation (5-14) depends upon the roughness parameter h. Thus if the moisture dependence of the Fresnel reflectivity is known then a graphical study of X and Y defined as

$$X = \frac{T_{NBV}(\theta_o) - T_{NBH}(\theta_o)}{1 - \frac{1}{2}\left[T_{NBH}(\theta_o) + T_{NBV}(\theta_o)\right]} \qquad (5\text{-}15)$$

$$Y = 1 - \frac{1}{2}\left[T_{NBH}(\theta_o) + T_{NBV}(\theta_o)\right] \qquad (5\text{-}16)$$

can determine both the roughness parameters h and Q. The Figure 5-1 illustrates the determination of these parameters. The brightness temperature quantities defined by Equations (5-15) and (5-16) were calculated from observed off-nadir ($\theta_o = 35^o$) 21 cm brightness temperatures for different surface

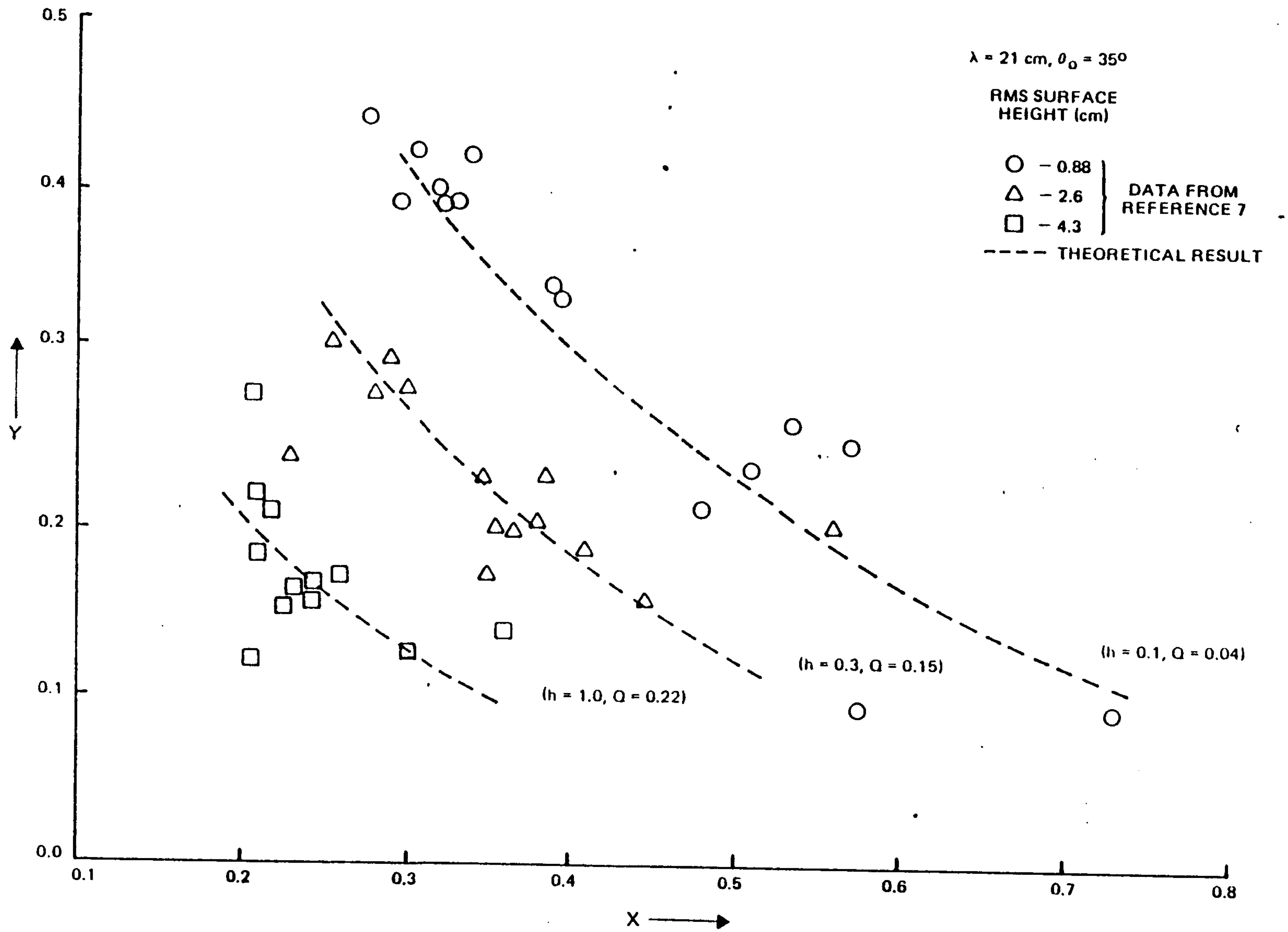

Figure 5-1. Graphical Determination of Roughness Parameters From Observed Off-Nadir Brightness Temperatures

roughness conditions (Reference 7). The theoretical curves were calculated using the dielectric constants of Miller Clay from the equations:

$$X = 2 \left[\frac{r_H(\theta_o) - r_V(\theta_o)}{r_H(\theta_o) + r_V(\theta_o)} \right] (1 - 2Q)$$

$$Y = \frac{1}{2} \left[r_H(\theta_o) + r_V(\theta_o) \right] \exp(-h \cos^2 \theta_o)$$

We see that by fitting the theoretical curve to the observation, one can estimate the roughness parameters. Note, that the required information for the determination of roughness parameters is the soil type and not the moisture values corresponding to the observed brightness temperatures. For remote sensing purposes a dual-polarization radiometer system seems to be appropriate for determining the surface roughness parameters.

SECTION 6 - DIURNAL VARIATION OF THE BRIGHTNESS TEMPERATURE

As stated in the introduction, the primary motivation for developing the present model was to gain soil moisture information from the brightness temperature. The observed brightness temperatures however, not only depend upon the soil moisture but also on the soil temperature. Since the soil temperatures show a diurnal variation, it is desirable to know the effect of diurnal soil temperature. Also, to compare the brightness temperatures observed under different soil temperatures conditions, we should have a model to normalize the observed brightness temperatures. This section contains an analysis of aforementioned problems.

The soil temperature explicitly appears in the calculation of the effective temperature, t , in Equation (2-3) as:

$$t = \int_0^\infty T(z)\, W(z)\, dz \qquad (6\text{-}1)$$

where the weighting function, W(z) , has been defined as:

$$W(z) = \gamma_a(z) \exp\left(-\int_0^z \gamma_a(z')\, dz'\right) \qquad (6\text{-}2)$$

It can easily be verified that the weighting function satisfies the normalization condition:

$$\int_0^\infty W(z)\, dz = 1$$

Since the soil temperature has been integrated over the whole depth, the actual sensitivity of Equation (6-1) to soil temperature variations is unclear. It is however understandable that this sensitivity will be determined by the nature of the weighting function.

If the weighting function is a monotonically decreasing function of depth, then by expanding the soil temperature in a Taylor series as:

$$T(z) = T(0) + \left.\frac{dT}{dz}\right|_0 \cdot z \tag{6-3}$$

(where $T(0)$ and $(dT/dz)|_0$ are, respectively, the surface temperature and slope), one can write the effective temperature of Equation (6-1) as:

$$t = t(0) + \left.\frac{dT}{dz}\right|_0 \langle z \rangle \tag{6-4}$$

where $\langle z \rangle$ is the sampling depth defined as:

$$\langle z \rangle = \int_0^{\infty} z \, W(z) \, dz \tag{6-5}$$

Consistent with the Taylor series expansion of Equation (6-3), one can interpret Equation (6-4) as the soil temperature at the sampling depth. With this interpretation, the diurnal variation of the brightness temperature should be determined by the variation of soil temperature at the sampling depth.

To gain further understanding of the sampling depth, let us assume that the absorption coefficient can be represented by (see Equation (2-5)):

$$\gamma_a(z) = \frac{4\pi}{\lambda} [a + b\, e^{-sz}] \tag{6-6}$$

where the coefficients a , b , and s are determined by the moisture profile. Using Equations (6-6) into (6-5) one can obtain an explicit formula for the sampling depth as (Reference 8, pages 308 and 940):

$$<z> = \frac{\lambda}{4\pi} \Phi \left(1,\ 1 + \frac{4\pi a}{\lambda s},\ \frac{4\pi b}{\lambda s}\right) \tag{6-7}$$

where Φ is the degenerate or confluent hypergeometric function.

From Equation (6-7), the following limiting cases are obtained:

$$<z> \approx \frac{\lambda}{4\pi}\left(\frac{1}{a+b}\right) \text{ for} \left(\frac{4\pi a}{\lambda s}\right) >> 1$$

$$<z> \approx \frac{\lambda}{4\pi}\left(\frac{1}{a}\right) \exp\left(-\frac{4\pi b}{\lambda s}\right) \text{ for } \left(\frac{4\pi a}{\lambda s}\right) << 1$$

The above limiting cases show that for small wavelenghts the sampling depth is primarily determined by the surface moisture, and for long wavelength the sampling depth depends upon the parameters of the moisture profile. It is also expected that the sampling depth will increase with the increase in wavelength, though a linear increase of sampling depth with the wavelength is not expected because the dielectric constants also depend upon the wavelength.

To provide further justification for Equation (6-4), we will now show that the effective temperature can be expressed as in Equation (6-4) without making the Taylor series expansion of Equation (6-3).

Integrating by parts, one can write Equation (6-1) as:

$$t = T(o) + \int_0^\infty \left(\frac{dT}{dz}\right) \exp\left(-\int_0^z \gamma_a(z')\, dz'\right) \tag{6-8}$$

where T(o) is the surface temperature.

The exponential term in Equation (6-8) is in general a rapidly decreasing function of depth. As a good approximation, we can write Equation (6-8) as:

$$t \approx T(o) + \left.\frac{dT}{dz}\right|_0 \int_0^\infty \exp\left(-\int_0^\infty \gamma_a(z')\, dz'\right) dz \tag{6-9}$$

where $(dT/dz)|_0$ is the surface slope.

One can now easily verify that the integral term in Equation (6-9) is the sampling depth. Thus Equation (6-9) is again equivalent to Equation (6-4).

From the above analysis, the effective temperature should be approximately equal to the soil temperature at the sampling depth. Also, the diurnal variation of the brightness temperatures for small wavelengths is expected to be larger than that for longer wavelengths.

To make a quantitative calculation for the effective temperature, one requires detailed information about the soil temperature and moisture. Under many circumstances, however, such detailed information is not available. In the following, we will derive an approximate expression for the effective temperature which does not require such detailed soil profile information.

Let us assume that the information available for calculating the effective temperature are the surface and the deep soil temperatures. The soil surface temperature can be obtained remotely via infrared spectroscopy. The deep soil temperature (i.e., soil temperature at the depth of about one meter) was chosen because this temperature does not show much diurnal variations.

The soil temperature profile can be expressed in a general form as:

$$T(z) = T_\infty + (T_0 - T_\infty)\, f(z) \qquad (6\text{-}10)$$

where T_0 and T_∞ are the soil surface and the deep soil temperature, respectively. The function $f(z)$ is an arbitrary function of depth subject to the conditions

$$\begin{aligned} f(z=0) &= 1 \\ f(z=\infty) &= 0 \end{aligned} \qquad (6\text{-}11)$$

Using Equation (6-10), the effective temperature Equation (6-1) can be written as:

$$t = T_\infty + (T_0 - T_\infty)\, C \qquad (6\text{-}12)$$

where

$$C = \int_0^\infty f(z)\, W(z)\, dz \qquad (6\text{-}13)$$

By writing the effective temperature as Equation (6-13), we have incorporated all unknown quantities into the constant, C . For Equation (6-13) to be useful we need to specify a value for C which will depend only upon the wavelength of the radiation. We will now consider the determination of this constant.

Examination of measured soil temperature profiles (Reference 4) shows that the difference between the surface and the deep soil temperature (soil temperature at the depth of about 1 meter) decreases as the moisture increases. Since for wet soils, this difference in temperature is small, we see that an exact value of C is not needed for approximate calculation of the effective temperature. For dry soils, however, the effective temperature will be sensitive to the choice of C because the temperature difference in Equation (6-12) is large. The above discussion suggests that if we calculate C using the profiles for dry soils then that value of C should also give reasonable estimates of effective temperature for the wet soils.

To verify the quantitative accuracy with which one can calculate the effective temperature using a fixed value of C , we used the soil profiles cited in Tables (3-1) or (3-2). The effective temperatures calculated using the Equations (6-1) and (6-12) are given in Table 6-1 for two different wavelengths. The value of C was calculated using the dry soil profiles. Although the calculated values of effective temperature from Equation (6-12) are somewhat higher than those obtained from Equation (6-1), the good agreement between the two effective temperatures is quite encouraging.

If we assume that the soil profiles used in our calculation, are representative of a general case, then an approximate formula for calculating the effective temperature will be:

$$t = T_\infty + 0.77\,(T_0 - T_\infty) \quad \text{for } \lambda = 1.55\text{cm}$$

$$t = T_\infty + 0.28\,(T_0 - T_\infty) \quad \text{for } \lambda = 21 \text{ cm}$$

It should be noted that the sampling depth information discussed previously has been implicitly incorporated into the above formulae through the calculation of

Table 6-1. Comparison of Exactly and Approximately Calculated Values of Effective Temperature

	λ = 1.55 cm		λ = 21 cm	
Profile	t from (6.1)	t from (6.12) C = 0.77	t from (6.1)	t from (6.12) C = 0.28
1	293.6	293.2	289.3	290.7
2	299.0	297.8	289.9	292.3
3	300.7	301.4	290.6	293.6
4	303.3	305.3	292.1	295.1
5	305.9	307.1	294.7	295.7
6	304.9	309.0	294.7	296.5
7	307.5	311.3	395.9	297.3
8	310.7	312.1	296.2	297.6

these constants. We see that the value of the constant increases as the wavelength decreases. For very long wavelengths, the effective temperature will be close to the deep soil temperature and for short wavelengths, the effective temperature will nearly equal to the surface temperature.

SECTION 7 - OUTLINE OF AN INVERSION ALGORITHM

In this section we will outline an algorithm for obtaining the soil moisture information from the observed 21 cm wavelength brightness temperatures over an agricultural terrain.

The brightness temperature observed over an agricultural terrain depends upon the soil moisture, the soil temperature and the roughness structure of the soil surface (References 4, 7, 9). The nature of these dependencies is discussed in the preceding sections and also by other investigators (References 1, 2, and 10). The soil temperature shows an areal and a diurnal variation and the roughness structure of the soil surface depends upon the cultivation practice of that area. To obtain the soil moisture information from the brightness temperature, we need to normalize the brightness temperature to account for the soil temperature and the roughness structure dependence of the brightness temperature. If we can successfully normalize the brightness temperature, then the normalized brightness temperatures will depend only upon the soil moisture. For a given wavelength of the radiation, the dependence of the normalized brightness temperature on the soil moisture is expected to be unique.

The starting point of the inversion algorithm is to find a unique relationship between the soil moisture and the normalized brightness temperature for the 21 cm wavelength radiation under smooth surface condition. For this purpose we used the observed brightness temperatures and the corresponding effective soil temperatures obtained by Newton (Reference 7) to calculate the normalized brightness temperatures defined in Equation (5-4). A linear regression study was performed between the normalized brightness temperatures (T^S_{NB}) and the average soil moistures in the 2.0 cm surface layer expressed in dimensionless percent field capacity (FC) units (Reference 4) by taking the conversion factor at 35 percent level to obtain the following relation:

$$FC = -1.49 + 169.6\ (1 - T^{S}_{NB}) \tag{7-1}$$

The correlation coefficient of the regression study was 0.956 and the standard deviation of the regression coefficient was 14.4.

The normalization of the brightness temperature to account for the diurnal soil temperature variation is discussed in Section 6. From the knowledge of the soil surface temperature (T_o) and the deep soil temperature (T_∞), one can calculate the effective soil temperature (t) from the equation

$$t = T_\infty + 0.28\ (T_o - T_\infty) \tag{7-2}$$

Remote infrared spectroscopy will give the soil surface temperature, and the deep soil temperature can be chosen approximately based upon the location and the season of observation.

The effect of surface roughness on the brightness temperature is discussed in Sections 4 and 5. We noted in Section 4 that the brightness temperatures of drier soil are less sensitive to the soil moisture but are affected by the roughness condition. Since the brightness temperature decreases with the increase in the moisture, one can stipulate that the highest value of the observed brightness temperature will correspond to a dry soil case. One can now use Equation (5-13) to calculate the roughness parameter of the surface (h) :

$$e^{h} = \frac{0.095}{(1 - T^{1}_{NB})} \tag{7-3}$$

where the numerical factor is due to the smooth surface brightness temperature and T^1_{NB} is the highest normalized brightness temperature.

Another way of estimating the roughness parameter will be to study the high and the low values of the brightness temperatures. If the range of the moisture values corresponding to the observed brightness temperature is known then the roughness parameter can be calculated from the following equation:

$$e^h = \frac{\Delta T^S_{NB}}{\Delta T_{NB}} \qquad (7-4)$$

where ΔT_{NB} is the difference of the observed high and low values of the normalized brightness temperature and ΔT^S_{NB} is the difference of the smooth surface normalized brightness temperature corresponding to the expected range of moisture values.

As discussed in Section 5, for an off-nadir dual-polarization radiometer system, one can calculate the roughness parameter by studying the sum and the difference of the normalized brightness temperatures (see Equations (5-15) and (5-16)). Also, for off-nadir observations, the average brightness temperature of two polarizations is nearly equal to its nadir value.

Once the roughness parameter of the agricultural terrain is known, the moisture values corresponding to each observed brightness temperature (T_{NB}) can be calculated from the Equation (5-13) and (7-1) as:

$$FC = -1.49 + 169.6\ (1 - T_{NB})\ e^h \qquad (7-5)$$

Thus, the inversion algorithm is the following:

Normalize the observed brightness temperatures using Equation (7-2) and calculate the roughness parameter of the agricultural terrain from Equations

(7-3) and (7-4). Using the roughness parameter calculate the soil moisture value corresponding to the normalized observed brightness temperatures from Equation (7-5).

The effectiveness of the inversion algorithm was studied using the brightness temperature data observed over bare agricultural fields during dawn and mid-day of March 18 and 22, 1975 (Reference 11). The soil surface temperatures were measured with a thermal infrared radiometer and a field crew performed measurements of the soil moisture and the texture. The target fields were 800 meters wide and 400 meters long. The primary surface condition was furrow.

Using the measured deep soil temperature $T_\infty = 13^oC$ and the observed soil surface temperatures T_o we normalized the observed brightness temperatures. From these normalized brightness temperatures we calculated the roughness parameter ($e^h = 1.9$), and then the soil moisture from Equation (7-5). In Figure (7-1) we show the comparison of the observed and the calculated values of the soil moisture, in the 2.0 cm surface layer. Also shown in the figure is the 1:1 line for the perfect agreement. We see that the calculated values are lower than the observed soil moistures. It appears that a better estimate for the observed soil moisture will be obtained if we add 10 percent field capacity to the calculated values from Equation (7-5). Considering the simplicity, the effectiveness of the inversion algorithm is quite encouraging. It should be noted that if soil moisture is expressed in units other than field capacity then the numerical factors appearing in Equations (7-1) and (7-5) will be different. Since the fundamental quantity which appears in the radiative transfer equation is the dielectric constant, it is expected that the most appropriate unit of soil moisture should be the one for which the dielectric constant curve does not depend upon soil type.

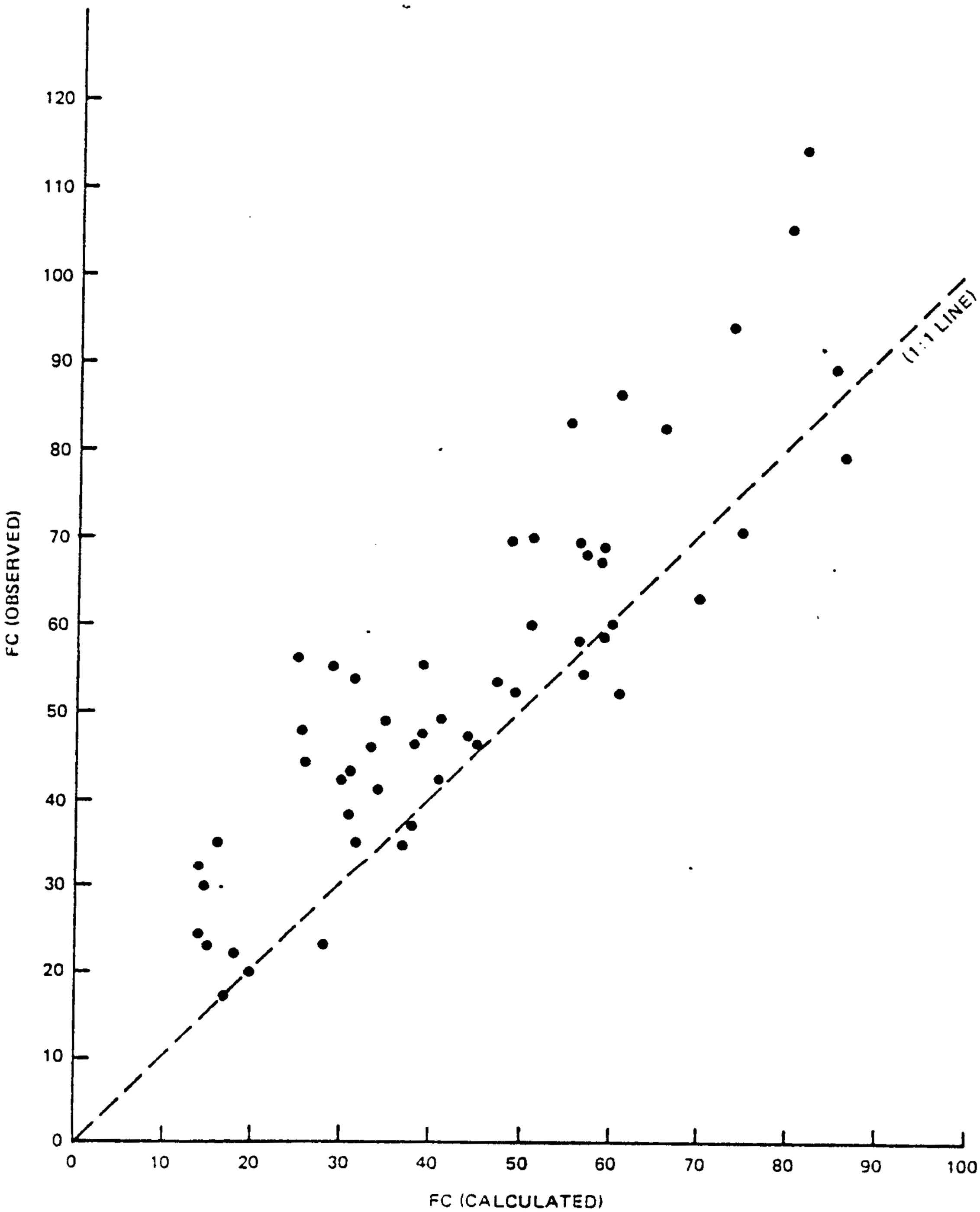

Figure 7-1. Comparison of Observed and Calculated Values of Soil Moisture in the 2 cm Surface Layer

APPENDIX A - SOURCE LISTING OF THE MODEL

```
//Z83JCSA3 JOB (S00141604A.T.L00000.001H00).007,MSGLEVEL=(2,0)
//*CSC
//*MODEL
// EXEC FORTRANG
//SOURCE.SYSIN DD *
      REAL*4 UPISOL(100)
      REAL*4 ASOIL(100)
      REAL*4 LAMDA,IOSNO,MUI
      COMPLEX DSOIL,AMO
      LOGICAL*1 L8
      COMMON/NO/NMAX2
      COMMON/SET1/NLMAX,Y(100),SM(100),TEMP(100)
      COMMON/COM1/XSNO(100),XSOL(100),XMAX,LAMDA
      COMMON/DUMY/S1(100),S2(100)
      COMMON/DUMYP/XD(1000),YD(1000)
      COMMON/CT/CT1,CT2,CT3,CT4,CT5
      COMMON/CM/CM1,CM2,CM3,CM4,CM5
      COMMON/LOGI/L8
      PI=3.14159
C
 10   CONTINUE
C
C     IF L8 IS TRUE THEN DEPTH VARIATION OF MOISTURE AND TEMP. IN SOIL
C     IS  NOT   KNOWN ANALYTICALLY
C
      L8=.TRUE.
      IF (.NOT.L8) READ(5,750) CM1,CM2,CM3,CM4,CM5
      IF (.NOT.L8) READ(5,750) CT1,CT2,CT3,CT4,CT5
C
      IF (L8) CALL SOLSET(&1111)
      WRITE (6,770)
C
      NMAX2=100
 500  CONTINUE
      LAMDA=1.55
      WRITE (6,450) LAMDA
 450  FORMAT(/,3X,'WAVELENGTH=',F10.2)
 400  CONTINUE
C
      THETAI=0.00
      XMAX=3.5*LAMDA
      IF (LAMDA.LT.4.0) XMAX=20.0*LAMDA
C
C    SET UP DEPTH GRID IN SOIL LAYER
C
```

```
      X=0.0
      IF (.NOT.LR) SM(NMAX2)=FNSM(X)
      CALL SOLGRD
C
C     USING THE GRID FIND MOISTURE AND TEMP AT GRID POINTS
C
C     CALCULATE THE SOIL PARAMETERS AT THE GRID POINTS
C
      CALL SOLPRO
      WRITE (6,625) SM(NMAX2),TEMP(NMAX2)
      AMD=DSOIL(NMAX2)
      WRITE (6,112) AMD
 112  FORMAT(3X,'TOP DIEL CONS=',2F10.3)
 625  FORMAT(///,20X,' TOP SOIL MOISTURE AND TEMPERATURE',2F10.2)
C
C
 100  CONTINUE
C
      MUI=COS(THETAI*PI/180.)
 300  CONTINUE
      CALL ABSORP(LAMDA,MUI,ASOIL)
      WRITE (6,760) ASOIL(NMAX2)
 760  FORMAT(/,3X,'TOP LAYER ABSORPTION/LENGTH=',E13.4)
      PMAX=1.0
      PARM=1.0
      DO 200 I=1,NMAX2
      CALL TAU(XSOL,ASOIL,I,NMAX2,T)
      T1=0.00
      IF (T.LT.40.) T1=EXP(-T)
      UPISOL(I)=TEMP(I)*T1*ASOIL(I)
 200  CONTINUE
      CALL FIND(LAMDA,XSOL,UPISOL,NMAX2,NEED)
      CALL TAU(XSOL,UPISOL,NEED,NMAX2,UPIO)
      WRITE (6,770)
 770  FORMAT(///,3X,'*******************************************************')
      WRITE (6,780)
 780  FORMAT(///,9X,'SMOOTH TRANS',1X,'ROUF TRANS',3X,'ROUGHNESS',5X,
     2'EFF SOIL TEMP',2X,'SMOOTH T.B.',4X,'ROUF T.B.')
 250  CONTINUE
      CALL REFIND(MUI,HHSOL,VVSOL,PARM,HISOL,VISOL)
      THSOL=1.-HHSOL
      THISOL=1.-HISOL
      TVSOL=1.-VVSOL
      TVISOL=1.-VISOL
      THHH=THSOL*UPIO
```

```
      TRVV=TVSOL*UPIO
      TRHH1=THISOL*UPIO
      TRVV1=TV1SOL*UPIO
      WRITE (6,775) THSOL,TH1SOL,PARM,UPIO,TRHH,TRHH1
  775 FORMAT(/,3X,6F15.3)
      PARM=PARM+0.20
      WRITE (6,785)
      WRITE (6,785)
  785 FORMAT(/,3X,'=====================================================')
  750 FORMAT(5F10.3)
      GO TO 10
  111 STOP
      END
      SUBROUTINE FIND(AL,X,Y,NG,N)
      REAL*4 X(1),Y(1)
      A=2.5*AL
      A=Y(NG)
      DO 100 J=1,NG
      I=NG+1-J
      B=Y(I)/A
      IF (B.LT.0.002) GO TO 200
  100 CONTINUE
  200 N=I
      RETURN
      END
      FUNCTION FNSM(X)
C
C     THE ANALYTIC FUNCTION FOR SOIL MOISTURE
C     X=0 IS AT THE TOP OF SOIL AND IT IS INCREASINS AS THE DEPTH
C     INCREASES
C     SEE SOLPRO
C
C     SEE SOIL GRID
      COMMON/CM/CM1,CM2,CM3,CM4,CM5
      FNSM=0.00
      Y=X
      FNSM=CM1
      RETURN
      END
      FUNCTION FNTP(X)
C
C     ANALYTIC FUNCTION FOR TEMPERATURE OF SOIL AT DEPTH X
C     X=0 IS AT THE TOP OF SOIL AND INCREASES WITH DEPTH
C     SEE SOLPRO
C     SEE SOIL GRID
```

```
C
C
C
      COMMON/CT/CT1,CT2,CT3,CT4,CT5
      ENTP=0.00
      Y=X
      E1=0.0
      X1=CT3*Y
      IF (X1.LT.10.) E1=EXP(-X1)
      ENTP=CT1+CT2*E1
      RETURN
      END
      SUBROUTINE FEBT(N,X)
C     FEBRURY TEMP ADJUSTMENT
      REAL*4 X(1)
      DO 100 I=1,N
 100  X(I)=X(N)+(X(I)-X(N))/2.20
      RETURN
      END
      SUBROUTINE SOLGRD
C
C     SETTING UP GRID IN SOIL LAYER
C
C     NOTE THAT THE GRID IS INCREASING TOWARDS THE SURFACE I.E.
C     (-) INFINITY  TO ZERO       <<<<<<<
C
      LOGICAL*1 L8
      COMMON/NO/NMAX2
      COMMON/SET1/NLMAX,Y(100),SM(100),TEMP(100)
      COMMON/COM1/XSNO(100),XSOL(100),XMAX,LAMDA
      COMMON/LOGI/L8
      IF (L8) CAL=SM(1)
      IF (.NOT.L8) CAL=SM(NMAX2)
      IF (CAL.LE.0.0) CAL=0.50
      RO1=0.001
      XSOL(1)=-XMAX
      PAS=ALOG(XMAX*CAL/RO1)/NMAX2
      DO 10 I=2,NMAX2
      ZI=NMAX2-I
      XSOL(I)=-RO1/CAL*EXP(PAS*ZI)
 10   CONTINUE
      XSOL(NMAX2)=0.00
      RETURN
      END
      SUBROUTINE SOLPRO
```

```
C
C     CALCULATES  THE SOIL MOISTURE AND TEMPERATURE  AT GRID POINTS
C
      REAL*4 ARG(6),VAL(6)
      LOGICAL*1 L8
      COMMON/COM1/XSNO(100),XSOL(100),XMAX,LAMDA
      COMMON/NO/NMAX2
      COMMON/SET1/NLMAX,Y(100),SM(100),TEMP(100)
      COMMON/DUMY/S1(100),S2(100)
      COMMON/LOGI/L8
      IF (.NOT.L8) GO TO 100
      DO 10 I=1,NLMAX
      S1(I)=SM(I)
      S2(I)=TEMP(I)
   10 CONTINUE
      NMAX21=NMAX2-1
      DO 200 I=1,NMAX21
      XXX=ABS(XSOL(I))
      CALL ATSM(XXX,Y,S1,NLMAX,1,ARG,VAL,6)
      CALL ALI(XXX,ARG,VAL,YYY,6,1.0E-02,IER)
      SM(I)=YYY
      CALL ATSM(XXX,Y,S2,NLMAX,1,ARG,VAL,6)
      CALL ALI(XXX,ARG,VAL,YYY,6,1.0E-02,IER)
      TEMP(I)=YYY
  200 CONTINUE
      SM(NMAX2)=S1(1)
      TEMP(NMAX2)=S2(1)
      RETURN
  100 CONTINUE
      DO 300 I=1,NMAX2
      XXX=ABS(XSOL(I))
      SM(I)=FNSM(XXX)
      TEMP(I)=FNTP(XXX)
  300 CONTINUE
      RETURN
      END
      SUBROUTINE TAU(X,Y,I,IMAX,T)
C
C     THIS SUBROUTINE CALCULATES THE OPTICAL DEPTH
C     X ARE THE ABSISSA VALUES AND Y ARE RESPECTIVE FUNCTION VALUES
C     INTEGRATION IS DONE FROM ( X(I), Y(I) )   TO  (X(IMAX), Y(IMAX))
C     INTEGRATION IS DONE Y SIMPSON RULE
C
      REAL*4 X(1),Y(1)
      REAL*4 ARG(6),VAL(6)
```

```
      COMMON/DUMYP/XD(1000),YD(1000)
C
      DELX=X(IMAX)-X(I)
      IO=IMAX-I
      IF (IO.EQ.0) GO TO 900
      IF (DELX.LT.3.0) IDEV=301
      IF (DELX.LT.2.0) IDEV=201
      IF (DELX.LT.1.0) IDEV=101
      IF (DELX.LT.0.5) IDEV=51
      IF (DELX.LT.0.3) IDEV=31
      IF (DELX.LT.0.2) IDEV=21
      IF (DELX.LT.0.1) IDEV=11
      IF (DELX.GE.3.0) IDEV=351
      IDEV1=IDEV-1
      DELX=DELX/FLOAT(IDEV1)
C
C     SET UP INITIAL AND FINAL VALUES
C     INTERPOLATE FOR EQUALLY SPACED GRID
C
      XD(1)=X(I)
      YD(1)=Y(I)
      DO 100 J=1,IDEV1
      XD(J+1)=XD(J)+DELX
 100  CONTINUE
      DO 200 J=2,IDEV1
      XXX=XD(J)
      CALL ATSM(XXX,X,Y,IMAX,1,ARG,VAL,6)
      CALL ALI(XXX,ARG,VAL,YYY,6,2.0E-04,IER)
      YD(J)=YYY
 200  CONTINUE
      XD(IDEV)=X(IMAX)
      YD(IDEV)=Y(IMAX)
C
      T=SIMPS(DELX,YD,IDEV)
C
      RETURN
C
 900  T=0.00
C
      RETURN
      END
      FUNCTION SIMPS(DEL,F,N)
      REAL*8 A
C
C     SIMPSON RULE INTEGRATION
```

```
C
      REAL*4 F(1)
      N1=N-1
      A=0.0D0
      DO 10 I=2,N1,2
 10   A=A+4.0D0*F(I)
      DO 20 I=3,N1,2
 20   A=A+2.0D0*F(I)
C
      SIMPS=DEL/3.*(F(1)+A+F(N))
C
      RETURN
      END
      SUBROUTINE ABSORP(LAMDA,MUI,ASOIL)
C
C     CALCULATES THE SOIL ABSORPTION LENGTH
C     SEE BURKE PARIS .NASA TECH NOTE .JSC
C
      REAL*4 LAMDA,MUI,ASOIL(1)
      COMPLEX DSOIL
      COMMON/NO/NMAX2
      PI=3.14159
      SI=SORT(1.-MUI*MUI)
      DO 100 I=1,NMAX2
      R1=REAL(DSOIL(I))
      R2=AIMAG(DSOIL(I))
      A1=R1-SI*SI
      A2=(R2/A1)**2
      BETA=SORT(0.5*A1*(1.+SORT(1.+A2)))
      ALFA=0.5*R2/BETA
      ASOIL(I)=4.*PI*ALFA/LAMDA
 100  CONTINUE
      RETURN
      END
      FUNCTION DSOIL(I)
C
C     THIS FUNCTION PROVIDES THE DIELECTRIC CONSTANT FOR SOIL
C
      COMPLEX DSOIL
      REAL*4 LAMDA,R211(9),R212(9),SM1(9)
      REAL*4 ARG(6),VAL(6)
      COMMON/COM1/XSNO(100),XSOL(100),XMAX,LAMDA
      COMMON/SET1/NLMAX,Y(100),SM(100),TEMP(100)
      DATA SM1/0.0,5.0,10.,15.,18.,20.,22.,24.,30./
      DATA R211/3.,4.5,6.,7.5,9.,11.,14.,18.,28./
```

```
      DATA R212/0.2,0.75,1.,1.5,2.,2.8,3.5,4.,7./
      YYY=SM(I)
      IF (YYY.LT.0.) GO TO 600
      IF (LAMDA.LE.1.60) GO TO 200
      IF (LAMDA.GT.1.60.AND.LAMDA.LE.3.3) GO TO 300
      IF (LAMDA.GT.3.3.AND.LAMDA.LE.22.) GO TO 400
      IF (LAMDA.GT.22.) GO TO 600
  200 R1=2.64+0.11*YYY
      R2=0.084*YYY
      IF (YYY.LT.7.1) GO TO 500
      R1=-2.1+0.776*YYY
      IF (YYY.LT.10.3) GO TO 500
      R2=-5.11+0.585*YYY
      IF (YYY.LT.19.) GO TO 500
      R1=7.85+0.25*YYY
      R2=0.26+0.29*YYY
      GO TO 500
  300 R1=2.5+0.22*YYY
      R2=0.17*YYY
      IF (YYY.LT.11.5) GO TO 500
      R1=-12.2+1.5*YYY
      R2=-1.5+0.35*YYY
      GO TO 500
  400 IF (YYY.GE.11.5) GO TO 410
      R1=2.56+0.298*YYY
      R2=0.060*YYY
      GO TO 500
  410 R1=-9.9+1.38*YYY
      R2=-1.44+0.185*YYY
  500 DSOIL=CMPLX(R1,R2)
      RETURN
  600 WRITE (6,700)
  700 FORMAT(/////,20X,'$$$$$  SOIL DIELECTRIC CONSTANT IN ERROR ')
      DSOIL=CMPLX(1.,1.)
      RETURN
      END
      SUBROUTINE REFIND(MUI,HH,VV,PARM,HH1,VV1)
C
C     CALC OF HH REFLECTIVITY
C     REF FOR AIR SOIL OR AIR SNOW INTERFACE
C     PARM SPECIFYS THE SURFACE ROUGHNESS
C     SEE BURKE AND PARIS /NASA TECH NOTE, JSC
C
      COMPLEX DSOIL,DSNOW,HN,HD,VN,VD,R,RP
      REAL*4 MUI
```

```
      COMMON/NO/NMAX2
C
C
      R=DSOIL(NMAX2)
      SI=SQRT(1.-MUI*MUI)
      R1=REAL(R)
      R2=AIMAG(R)
      BETA1=R1-SI*SI
      BETA2=(R2/BETA1)**2
      BETA=SQRT(0.5*BETA1*(1.+SQRT(1.+BETA2)))
      ALFA=0.5*R2/BETA
      RP=CMPLX(BETA,ALFA)
      HN=RP-MUI
      HD=RP+MUI
      HH=CABS(HN/HD)*CABS(HN/HD)
      VN=RP-R*MUI
      VD=RP+R*MUI
      VV=CABS(VN/VD)*CABS(VN/VD)
      IF (PARM.EQ.0.00) GO TO 100
      DAMP=REAL(R)-SI*SI
      HH1=HH*EXP(-PARM)
      VV1=VV*EXP(-PARM)
      RETURN
 100  HH1=HH
      VV1=VV
      RETURN
      END
      SUBROUTINE SOLSET(*)
C
C     READ SOIL MOISTURE AND TEMPERATURE DATA
C     X=0 AT TOP AND INCREASING AS DEPTH INCREASES
C     DATA VALUES ARE AT DEPTH X
C     IF TOP SOIL MOISTURE AND TEMPERATURE IS NOT GIVEN THEN
C     THROUGH QUADRATIC POLYNOMIAL  THE DATA WILL BE INTERPOLATED BUT
C     DEEP SOIL MOISTURE AND TEMPERATURE MUST BE PROVIDED
C     SEE THE FORMAT BY WHICH THE DATA WILL BE READ
C
      REAL*4 TITLE(80)
      COMMON/SET1/NLMAX,Y(100),SM(100),TEMP(100)
      COMMON/COM1/XSNO(100),XSOL(100),XMAX,LAMDA
C
      READ(5,10,END=699) (TITLE(I),I=1,75)
      WRITE (6,10) (TITLE(I),I=1,75)
      READ(5,20) NL
C
```

```
C
      DO 40  I=1,NL
      READ(5,30,END=600) Y(I),SM(I),TEMP(I)
 40   CONTINUE
C
      XMAX=75.0
      NLMAX=NL
      IF (Y(1).EQ.0.0) GO TO 500
      NLMAX=NLMAX+1
      IF (NLMAX.GT.99) GO TO 600
C
C     BACKWORD INTERPOLATION TO OBTAIN VALUE AT X=0
C
      SMM=SM(1)-0.5*(SM(2)-SM(1))
      TPP=TEMP(1)-0.5*(TEMP(2)-TEMP(1))
C
 500  IF (Y(NL).GE.XMAX) GO TO 700
      NLMAX=NLMAX+1
      IF (NLMAX.GT.99) GO TO 600
      Y(NLMAX)=XMAX
      SM(NLMAX)=SM(NL)
      TEMP(NLMAX)=TEMP(NL)
 700  IF (Y(1).EQ.0.0) GO TO 450
      DO 400 I=1,NL
 400  XSOL(I)=Y(I)
      Y(1)=0.00
      DO 410 I=1,NL
 410  Y(I+1)=XSOL(I)
      DO 420 I=1,NL
 420  XSOL(I)=SM(I)
      SM(1)=0.00
      IF (SMM.GE.0.) SM(1)=SMM
      DO 425  I=1,NL
 425  SM(I+1)=XSOL(I)
      DO 430 I=1,NL
 430  XSOL(I)=TEMP(I)
      TEMP(1)=TPP
      DO 440 I=1,NL
 440  TEMP(I+1)=XSOL(I)
 450  CONTINUE
      RETURN
 10   FORMAT(75A1)
 20   FORMAT(I5)
 30   FORMAT(3F10.2)
 600  CONTINUE
```

```
      IF (XMAX.LT.0.00) WRITE (6,730)
      IF (NLMAX.GT.99) WRITE (6,710)
 710  FORMAT(15X,' NO OF POINTS IN SOIL DATA SET TOO LARGE')
 720  FORMAT(20X,' SOIL DEPTH IN DATA SET TOO LARGE ')
 730  FORMAT(20X,' SOIL DEPTH HAS NOT BEEN SPECIFIED PROPERLY')
 699  CONTINUE
      RETURN 1
      END
// EXEC LINKGO,REGION.GO=150K
//GO.SYSUDUMP DD SYSOUT=A
//GO.DATA5 DD *
  SIMULATED 2 DAY AFTER (DAY 3 MORNING MOISTURE&AFTERNOON TEMP)
   15
  0.25      27.50      293.7
  0.50      25.7       292.5
  2.0       22.6       291.2
  4.0       21.3       289.8
  7.0       20.2       288.5
  12.5      19.8       286.8
  17.5      19.5       285.5
  25.0      19.7       285.0
  35.0      18.5       285.8
  45.0      17.5       286.1
  55.0      16.3       286.4
  65.0      15.3       286.8
  75.0      13.9       287.6
  85.0      11.0       288.3
  95.0      9.5        289.0
   3/5/71.   3 DAYS  AFTER IRR
   18
  0.25       20.7       293.7
  0.5        21.5       292.5
  1.5        19.8       291.6
  2.5        19.8       290.9
  3.5        19.1       290.1
  4.5        18.9       289.6
  6.0        19.0       288.9
  8.0        19.1       287.9
 12.5        18.8       286.5
 17.5        18.8       285.1
 25.0        18.6       285.0
 35.0        18.2       285.0
 45.0        17.3       285.7
 55.0        16.2       286.3
 65.0        15.8       286.9
```

75.0	14.0	287.7
85.0	11.2	285.5
95.0	9.6	289.2

3/6/71. 4 DAYS AFTER IRR.
18

0.25	15.7	299.4
0.5	16.3	297.7
1.5	16.5	294.8
2.5	17.2	293.0
3.5	17.3	291.7
4.5	17.4	290.7
6.0	17.5	289.3
8.0	17.9	287.5
12.5	18.0	285.1
17.5	18.2	283.4
25.0	18.3	283.6
35.0	18.0	283.8
45.0	17.2	284.7
55.0	16.2	285.6
65.0	15.8	286.6
75.0	14.2	287.5
85.0	11.4	288.4
95.0	9.8	289.2

3/7/71 . 5 DAYS AFTER IRR
18

0.25	8.7	303.5
0.5	11.7	300.4
1.5	15.3	297.0
2.5	16.3	294.8
3.5	16.7	293.4
4.5	17.0	292.0
6.0	17.3	290.2
8.0	17.4	288.0
12.5	17.3	285.8
17.5	17.7	283.7
25.0	17.9	283.6
35.0	17.8	283.6
45.0	17.1	284.5
55.0	16.2	285.4
65.0	15.9	286.2
75.0	14.3	287.1
85.0	11.5	288.0
95.0	10.0	288.8

3/8/71 . 6 DAYS AFTER IRR
18

0.25	5.7	308.1
0.50	9.0	304.1
1.5	14.0	300.0
2.5	15.1	297.5
3.5	15.7	295.9
4.5	15.8	294.4
6.0	16.1	291.0
8.0	16.5	289.2
12.5	16.7	286.7
17.5	17.3	284.3
25.0	17.6	284.1
35.0	17.6	283.9
45.0	17.0	284.6
55.0	16.2	285.2
65.0	16.0	285.8
75.0	14.4	286.8
85.0	11.7	287.7
95.0	10.2	288.6

3/10/71. 8 DAYS AFTER IRR

18

0.25	3.4	310.9
0.5	5.5	307.8
1.5	12.0	303.1
2.5	14.1	300.4
3.5	14.7	298.8
4.5	15.0	297.4
6.0	15.3	295.3
8.0	15.6	292.5
12.5	15.9	289.8
17.5	16.7	286.9
25.0	17.2	286.4
35.0	17.3	285.9
45.0	16.8	286.2
55.0	16.2	286.5
65.0	16.1	286.9
75.0	14.6	287.6
85.0	12.0	288.4
95.0	10.6	289.4

3/14/71. 12 DAYS AFTER IRR.

18

0.25	2.7	312.6
0.5	4.1	308.0
1.5	9.7	302.5
2.5	12.7	299.5
3.5	13.7	298.2

4.5	14.0	296.2
6.0	14.5	295.7
8.0	14.9	294.1
12.5	15.2	291.4
17.5	15.9	288.7
25.0	16.4	288.0
35.0	16.6	287.3
45.0	16.3	287.6
55.0	15.9	288.0
65.0	16.0	288.3
75.0	14.7	288.5
85.0	12.4	288.8
95.0	11.4	289.1

3/18/71. 16 DAYS AFTER IRR

18

0.25	2.1	316.0
0.5	2.8	312.1
1.5	5.9	305.7
2.5	9.5	301.8
3.5	11.8	300.2
4.5	12.8	299.0
6.0	13.5	297.6
8.0	14.2	295.9
12.5	14.4	292.8
17.5	15.2	290.1
25.0	15.6	289.3
35.0	15.6	288.6
45.0	15.2	288.7
55.0	14.8	288.8
65.0	14.9	288.9
75.0	13.9	289.0
85.0	12.2	289.2
95.0	12.4	289.3

3/25/71. 23 DAYS AFTER IRR.

16

0.25	1.9	318.4
.5	2.2	317.4
2.0	4.9	305.6
3.	7.1	303.1
4.	8.7	301.6
6.	11.5	298.4
7.	12.5	297.4
8.	13.3	296.6
10.	14.0	295.0
15.	14.4	292.0

```
  20.          14.8        290.5
  30.          15.0        290.0
  50.          14.8        289.0
  70.          14.2        289.0
  90.          13.6        289.0
 100.          12.8        289.0
   4/8/71. 37 DAYS AFTER IRRIGATION
    13
    0.25       1.40       322.6
    0.75       1.90       321.5
    1.50       2.50       317.0
    2.50       3.50       311.5
    3.50       4.70       308.8
    4.50       5.80       307.0
    6.0        7.40       304.3
    8.00       9.20       301.7
    12.0       11.2       298.1
    16.0       12.4       295.2
    32.0       13.0       294.0
    64.0       12.5       292.0
    100.       12.0       290.0
  MID DAY TEMP PROFILE DAWN MOISTURE PROFILE  OF DAY 37
    13
    0.25       2.70       322.6
    0.75       2.80       321.5
    1.50       3.40       317.
    2.50       4.60       311.5
    3.50       5.80       308.8
    4.50       6.80       307.0
    6.00       8.10       304.3
    8.0        9.80       301.7
    12.0       11.2       298.1
    16.0       12.4       295.2
    32.0       13.0       294.0
    64.0       12.5       292.0
    100.       12.0       290.0
/*
/*
/*
/*
/*
/*
/*
/*
//
```

APPENDIX B - SOURCE LISTING OF THE BURKE-PARIS MODEL.

```
//ZBBJCSA3 JOB (S00141604A.T.L00000.001H001.007,MSGLEVEL=(2,0))
//*BURKE
//*PARIS
// EXEC FORTRANG
//SOURCE.SYSIN DD *
C     ..................................................................
C
C                BRIGHTNESS TEMPERATURE   USING THE MODEL    OF
C                             BURKE    &    PARIS
C
C       USER NEED TO SPECIFY THE FOLLOWING
C       (1)  ANGLE OF OBSERVATION          THETAI
C       (2)  WAVELENGTH       LAMDA       IN CM
C       (3)  LOGICAL VARIABLE    LR
C
C     ..................................................................
      REAL*4 TITLE(70)
      REAL*4 LAMDA,IDSNO,MU
      LOGICAL*1 L1,L2,L3,L4,L5,L6,L7,L8,L9,LR
      COMMON/NO/NMAX2
      COMMON/SET1/NLMAX,Y(100),SM(100),TEMP(100)
      COMMON/COM1/XSMO(100),XSOL(100),XMAX,LAMDA
      COMMON/DUMY/S1(100),S2(100)
      COMMON/CT/CT1,CT2,CT3,CT4,CT5
      COMMON/CM/CM1,CM2,CM3,CM4,CM5
      COMMON/LOGI/L1,L2,L3,L4,L5,L6,L7,L8,L9,LR
C     <<.................
C
C     << ......................
C
      PI=3.14159
C
C     IF LR IS TRUE THEN DEPTH VARIATION OF MOISTURE AND TEMP. IN SOIL
C     IS  NOT   KNOWN ANALYTICALLY
C      IF LR IS TRUE THEN SEE SOLSET FOR DATA SET FORMAT
C       IF LR IS FALSE THEN SEE FUNCTIONS  FNSM & FNTP
C
C
C
      LR=.TRUE.
C
C
      NMAX2=100
C
 500  CONTINUE
```

```
      IF (.NOT.L8) READ(5,750,END=999) CM1,CM2,CM3,CM4,CM5
      IF (.NOT.L8) READ(5,750,END=999) CT1,CT2,CT3,CT4,CT5
C
 200  CONTINUE
C     LAMDA IS WAVELENGTH IN CM.
      LAMDA=1.55
C     PARM IS SURFACE ROUGHNESS PARAMETER
C     THETAI  IS ANGLE OF OBSERVATION (DEGREE)
      PARM=1.0
      PMAX=1.0
C
C     SET UP DEPTH GRID IN SOIL LAYER
C
C     USING THE GRID FIND MOISTURE AND TEMP AT GRID POINTS
C     CALCULATE THE SOIL PARAMETERS AT THE GRID POINTS
C
      XMAX=3.5*LAMDA
      IF (LAMDA.LT.4.0) XMAX=20.0*LAMDA
      IF (L8) CALL SOLSET(&999)
      X=0.0
      IF (.NOT.L8) SM(1)=FNSM(X)
      CALL SOLGRD
C
C
      DO 450 I=1,NMAX2
      IF (XSNO(I).LT.1.1) IO=I
      IF (XSNO(I).GE.1.1) GO TO 470
 450  CONTINUE
 470  AVESM=(SM(1)+SM(IO))/2.
      IF (.NOT.L8) AVESM=(FNSM(0.)+FNSM(1.))/2.
      WRITE (6,625) AVESM,TEMP(1)
C
      WRITE (6,660) LAMDA
      WRITE (6,700)
      WRITE (6,800)
C
 100  CONTINUE
      CALL SOLPRO
      DO 401 J=1,99
      IF (SM(J).LT.0.) GO TO 225
 401  CONTINUE
 400  CONTINUE
      THETAI=0.00
      WRITE (6,680) PARM
      DEGI=THETAI*PI/180.
```

```
      MUI=COS(DEGI)
      CALL RPM(MUI,PARM,XSNO,TEMP,NMAX2,TH,THI,TV,TVI)
      WRITE (6,751) THETAI,TH,THI,TV,TVI
C
 225  CONTINUE
      PARM=PARM+0.20
C
      WRITE (6,690)
      WRITE (6,695)
      GO TO 500
 999  CONTINUE
      WRITE (6,710) XSOL
      WRITE (6,710) XSNO
      WRITE (6,710)  TEMP
 1    FORMAT(70A1)
 625  FORMAT (//,20X,'FIELD CHARACTERISTIC :',/20X,'AVE SM=',F10.2,
     1/20X,'TOP SOIL TEMP=',F10.2)
 660  FORMAT(//,10X,' WAVE LENGTH =',F10.2,2X,'C.M.')
 680  FORMAT(//,10X,'SURFACE ROUGHNESS PARAMETER =',F10.3)
 690  FORMAT (//////,3X,'........................................')
 695  FORMAT(1H0)
 700  FORMAT(///,2X,'ANGLE',7X,'HORIZONTAL',13X,'VERTICAL',/17X,'R.T.',
     118X,'R.T.')
 710  FORMAT(/,3X,8E12.4)
 750  FORMAT(5F10.3)
 751  FORMAT(5F10.3,15X,2F10.2)
 800  FORMAT(//,12X,'SMOOTH',4X,'ROUGH',5X,'SMOOTH',4X,'ROUGH')
      STOP
      .END
      SUBROUTINE RPM(MUI,PARM,XSNO,TEMP,NMAX2,T3,T1,T4,T2)
      REAL*4 MUI,XSNO(1),TEMP(1)
      CALL REINDT(1,MUI,HH,VV,PARM,HH1,VV1)
C     ROUGH SURFACE TRANSMISSION COEFS
      TRANS1=1.-HH1
      TRANS2=1.-VV1
C     SMOOTH SURFACE TRANSMISSION COEFS
      TRANS3=1.-HH
      TRANS4=1.-VV
      WRITE (6,100) TRANS3,TRANS4
 100  FORMAT(20X,' FRESNEL TRANS=',2E13.4)
      G1=GAMA(1,MUI)
      X1=XSNO(2)-XSNO(1)
      CALL REINDT(2,MUI,HH,VV,PARM,HH1,VV1)
      TRANS5=1.-HH
      TRANS6=1.-VV
```

```
      F1=G1*X1
      F0=0.0
      IF (F1.LT.30.) F0=EXP(-F1)
      T1=TRANS1*(1.-F0)*(1.+HH*F0)*TEMP(1)
      T2=TRANS2*(1.-F0)*(1.+VV*F0)*TEMP(1)
      T3=TRANS3*(1.-F0)*(1.+HH*F0)*TEMP(1)
      T4=TRANS4*(1.-F0)*(1.+VV*F0)*TEMP(1)
      TRANHP=TRANS1*TRANS5
      TRANVP=TRANS2*TRANS6
      TRANSH=TRANS3*TRANS5
      TRANSV=TRANS4*TRANS6
      NMAX22=NMAX2-2
      DO 222 I=2,NMAX22
      I1=I+1
      G=GAMA(I,MUI)
      X1=XSNO(I+1)-XSNO(I)
      F1=G*X1
      IF (F1.LT.30.) F1=EXP(-F1)
      IF (F1.GE.30.) F1=0.0
      CALL REINDT(I1,MUI,HHP,VVP,PARM,HH1,VV1)
      T1=T1+TRANHP*TEMP(I)*(1.-F1)*(1.+HHP*F1)*F0
      T2=T2+TRANVP*TEMP(I)*(1.-F1)*(1.+VVP*F1)*F0
      T3=T3+TRANSH*TEMP(I)*(1.-F1)*(1.+HHP*F1)*F0
      T4=T4+TRANSV*TEMP(I)*(1.-F1)*(1.+VVP*F1)*F0
      F0=F0*F1
      IF (F0.LT.1.0E-40) F0=0.0
      TRANHP=TRANHP*(1.-HHP)
      TRANVP=TRANVP*(1.-VVP)
      TRANSH=TRANSH*(1.-HHP)
      TRANSV=TRANSV*(1.-VVP)
  222 CONTINUE
      RETURN
      END
      FUNCTION GAMA(I,MUI)
C
C     CALCULATES THE TOTAL EXTINCTION PER UNIT LENGTH
C     FOR  I TH LAYER
C     SEE BURKE AND PARIS   EQN 2 & 3
C
      COMPLEX DSOIL
      REAL*4 MUI,LAMDA
      COMMON/COM1/XSNO(100).XSOL(100),XMAX,LAMDA
      PI=3.14159
      DR=REAL(DSOIL(I))
      DI=AIMAG(DSOIL(I))
```

```
      DI2=DI*DI
      S=SQRT(1.-MUI*MUI)
      S2=S*S
      DRS=DR-S2
      DRS2=DRS*DRS
      BETA=SQRT(0.5*DRS*(1.+SQRT(1.+DI2/DRS2)))
      ALFA=0.5*DI/BETA
      GAMA=4.*PI*ALFA/LAMDA
      RETURN
      END
      SUBROUTINE REINDT(I,MUI,HH,VV,PARM,HH1,VV1)
C
C
C     CALC. FRESNEL REFLEC AT SURFACE I
C     I=1  CORRESPONDS TO SOIL AIR INTERFACE
C     I=2,3,... CORRESPONDS TO SURFACE BETWEEN LAYER 1 & 2   ETCOF SOIL
C
C     SEE BURKE PARIS FOR DATAIL
C     NASA TECH NOTE JSC
C
      REAL*4 MUI
      COMPLEX DSOIL,DSNOW,R,RP,HN,HD,VN,VD
      COMMON/NO/NMAX2
      R1=REAL(DSOIL(I))
      R2=AIMAG(DSOIL(I))
      IF (I.EQ.1) R3=1.00
      IF (I.GT.1) R3=REAL(DSOIL(I-1))
      IF (I.EQ.1) R4=0.00
      IF (I.GT.1) R4=AIMAG(DSOIL(I-1))
      SI=SQRT(1.-MUI*MUI)
      A1=R1-SI*SI
      A2=R3-SI*SI
      A3=(R2/A1)**2
      A4=(R4/A2)**2
      BETA1=SQRT(0.5*A1*(1.+SQRT(1.+A3)))
      BETA2=SQRT(0.5*A2*(1.+SQRT(1.+A4)))
       ALFA1=0.5*R2/BETA1
      ALFA2=0.5*R4/BETA2
      R=CMPLX(BETA1,ALFA1)
      RP=CMPLX(BETA2,ALFA2)
      HN=R-RP
      HD=R+RP
      HH=CABS(HN/HD)*CABS(HN/HD)
      IF (I.EQ.1) VN=R-RP*DSOIL(I)
      IF (I.EQ.1) VD=R+RP*DSOIL(I)
```

```
      IF (I.GT.1) VN=R*DSOIL(I-1)-RP*DSOIL(I)
      IF (I.GT.1) VD=R*DSOIL(I-1)+RP*DSOIL(I)
      VV=CABS(VN/VD)*CABS(VN/VD)
      IF (PARM.EQ.0.0.OR.I.GT.1) GO TO 100
      DAMP=R1-SI*SI
      HH1=HH*EXP(-PARM)
      VV1=VV*EXP(-PARM)
      RETURN
100   HH1=HH
      VV1=VV
      RETURN
      END
      FUNCTION FNSM(X)
C
C     THE ANALYTIC FUNCTION FOR SOIL MOISTURE
C     X=0 IS AT THE TOP OF SOIL AND IT IS INCREASINS AS THE DEPTH
C     INCREASES
C     SEE SOLPRO
C
C     SEE SOIL GRID
      COMMON/CM/CM1,CM2,CM3,CM4,CM5
      FNSM=0.00
      FNSM=CM1
      RETURN
      END
      FUNCTION FNTP(X)
C
C     ANALYTIC FUNCTION FOR TEMPERATURE OF SOIL AT DEPTH X
C     X=0 IS AT THE TOP OF SOIL AND INCREASES WITH DEPTH
C     SEE SOLPRO
C     SEE SOIL GRID
C
C
C
      COMMON/CT/CT1,CT2,CT3,CT4,CT5
      FNTP=0.00
      Y=X
      E1=0.0
      X1=CT3*Y
      IF (X1.LT.20.) E1=EXP(-X1)
      FNTP=CT1+CT2*E1
      RETURN
      END
      SUBROUTINE FEBT(N,X)
C     FEBRURY TEMP ADJUSTMENT
```

```
      REAL*4 X(1)
      DO 100 I=1,N
 100  X(I)=X(N)+(X(I)-X(N))/2.20
      RETURN
      END
      SUBROUTINE SOLGRD
C
C     SETTING UP GRID IN SOIL LAYER
C
C
C     SETS UP THE GRID IN X SPACE IN LOGARITHMIC MESH
C     X(1)=0.00     AND    INCREASING AS DEPTH INCREASES
C     XSNO IS THE REGULAR LOG GRID ANG XSOL ARE MID PINTS OF THIS GRID
C
C
      LOGICAL*1 L1,L2,L3,L4,L5,L6,L7,L8,L9,L0
      COMMON/NO/NMAX2
      COMMON/SET1/NLMAX,Y(100),SM(100),TEMP(100)
      COMMON/COM1/XSNO(100),XSOL(100),XMAX,LAMDA
      COMMON/LOGI/L1,L2,L3,L4,L5,L6,L7,L8,L9,L0
      CAL=SM(1)
      IF (CAL.LE.0.0) CAL=0.050
      R01=0.0010
      XSNO(1)=0.00
      PAS=ALOG(XMAX*CAL/R01)/NMAX2
      DO 100 I=2,NMAX2
      ZI=I
 100  XSNO(I)=R01/CAL*EXP(ZI*PAS)
C
C     THE MID PINTS CALC
C
      XSOL(1)=(XSNO(1)+XSNO(2))/2.
      NMAX21=NMAX2-1
      DO 200 I=2,NMAX21
      XSOL(I)=(XSNO(I)+XSNO(I+1))/2.
 200  CONTINUE
      RETURN
      END
      SUBROUTINE SOLPRO
C
C     CALCULATES  THE SOIL MOISTURE AND TEMPERATURE  AT GRID POINTS
C
      REAL*4 ARG(6),VAL(6)
      LOGICAL*1 L1,L2,L3,L4,L5,L6,L7,L8,L9,L0
      COMMON/COM1/XSNO(100),XSOL(100),XMAX,LAMDA
```

```
      COMMON/NO/NMAX2
      COMMON/SET1/NLMAX,Y(100),SM(100),TEMP(100)
      COMMON/DUMY/S1(100),S2(100)
      COMMON/LOGI/L1,L2,L3,L4,L5,L6,L7,L8,L9,L0
      IF (.NOT.L8) GO TO 100
      DO 10 I=1,NLMAX
      S1(I)=SM(I)
      S2(I)=TEMP(I)
   10 CONTINUE
      NMAX21=NMAX2-1
      DO 200 I=1,NMAX21
      XXX=ABS(XSOL(I))
      CALL ATSM(XXX,Y,S1,NLMAX,1,ARG,VAL,6)
      CALL ALI(XXX,ARG,VAL,YYY,6,1.0E-02,IER)
      SM(I)=YYY
      CALL ATSM(XXX,Y,S2,NLMAX,1,ARG,VAL,6)
      CALL ALI(XXX,ARG,VAL,YYY,6,1.0E-02,IER)
      TEMP(I)=YYY
  200 CONTINUE
      RETURN
  100 CONTINUE
      NMAX21=NMAX2-1
      DO 300 I=1,NMAX21
      XXX=ABS(XSOL(I))
      SM(I)=FNSM(XXX)
  300 CONTINUE
      DO 350 I=1,NMAX21
      XXX=ABS(XSOL(I))
      TEMP(I)=FNTP(XXX)
  350 CONTINUE
  710 FORMAT(3X,8E12.4)
      RETURN
      END
      FUNCTION DSOIL(I)
C
C     THIS FUNCTION PROVIDES THE DIELECTRIC CONSTANT FOR SOIL
C
      COMPLEX DSOIL
      LOGICAL*1 L1,L2,L3,L4,L5,L6,L7,L8,L9,L0
      REAL*4 LAMDA,R211(9),R212(9),SM1(9)
      REAL*4 ARG(6),VAL(6)
      COMMON/COM1/XSNO(100),XSOL(100),XMAX,LAMDA
      COMMON/SET1/NLMAX,Y(100),SM(100),TEMP(100)
      COMMON/LOGI/L1,L2,L3,L4,L5,L6,L7,L8,L9,L0
      DATA SM1/0.0,5.0,10.,15.,18.,20.,22.,24.,35./
```

```
      DATA R211/3.,4.5,6.,7.5,9.,11.,14.,18.,36./
      DATA R212/0.2,0.75,1.,1.5,2.,2.8,3.5,4.,8./
      YYY=SM(I)
      IF (YYY.LT.0.) GO TO 600
      IF (LAMDA.LE.1.55) GO TO 200
      IF (LAMDA.GT.1.55.AND.LAMDA.LE.3.3) GO TO 300
      IF (LAMDA.GT.3.3.AND.LAMDA.LE.22.) GO TO 400
      IF (LAMDA.GT.22.) GO TO 600
  200 R1=2.64+0.11*YYY
      R2=0.084*YYY
      IF (YYY.LT.7.1) GO TO 500
      R1=-2.1+0.776*YYY
      IF (YYY.LT.10.3) GO TO 500
      R2=-5.11+0.585*YYY
      IF (YYY.LT.19.) GO TO 500
      R1=7.85+0.25*YYY
      R2=0.26+0.29*YYY
      GO TO 500
  300 RETURN
  400 CONTINUE
      IF (YYY.GE.11.5) GO TO 410
      R1=2.56+0.298*YYY
      R2=0.06*YYY
      GO TO 500
  410 R1=-9.9+1.38*YYY
      R2=-1.44+0.185*YYY
  500 DSOIL=CMPLX(R1,R2)
      RETURN
  600 WRITE (6,700)
  700 FORMAT(/////,20X,'$$$$$  SOIL DIELECTRIC CONSTANT IN ERROR ')
      DSOIL=CMPLX(1.,1.)
      RETURN
      END
      SUBROUTINE SOLSET(*)
C
C     READ SOIL MOISTURE AND TEMPERATURE DATA
C     X=0 AT TOP AND INCREASING AS DEPTH INCREASES
C     DATA VALUES ARE AT DEPTH X
C     IF TOP SOIL MOISTURE AND TEMPERATURE IS NOT GIVEN THEN
C     THROUGH QUADRATIC POLYNOMIAL  THE DATA WILL BE INTERPOLATED BUT
C     DEEP SOIL MOISTURE AND TEMPERATURE MUST BE PROVIDED
C     SEE THE FORMAT BY WHICH THE DATA WILL BE READ
C
      REAL*4 TITLE(80)
      COMMON/SET1/NLMAX,Y(100),SM(100),TEMP(100)
```

```
      COMMON/COM1/XSNO(100),XSOL(100),XMAX,LAMDA
C
      READ(5,10,END=600) (TITLE(I),I=1,75)
      WRITE (6,10) (TITLE(I),I=1,75)
      READ(5,20) NL
C
C
      DO 40 I=1,NL
      READ(5,30,END=600) Y(I),SM(I),TEMP(I)
 40   CONTINUE
C
      IF (XMAX.LT.0.00) GO TO 600
      NLMAX=NL
      IF (Y(1).EQ.0.0) GO TO 500
      NLMAX=NLMAX+1
      IF (NLMAX.GT.99) GO TO 600
C
C    BACKWORD INTERPOLATION TO OBTAIN VALUE AT X=0
      SMM=SM(1)-0.5*(SM(2)-SM(1))
      TPP=TEMP(1)-0.5*(TEMP(2)-TEMP(1))
C
 500  IF (Y(NL).GE.XMAX) GO TO 700
      NLMAX=NLMAX+1
      IF (NLMAX.GT.99) GO TO 600
      Y(NLMAX)=XMAX
      SM(NLMAX)=SM(NL)
      TEMP(NLMAX)=TEMP(NL)
 700  IF (Y(1).EQ.0.0) GO TO 450
      DO 400 I=1,NL
 400  XSOL(I)=Y(I)
      Y(1)=0.00
      DO 410 I=1,NL
 410  Y(I+1)=XSOL(I)
      DO 420 I=1,NL
 420  XSOL(I)=SM(I)
      SM(1)=0.00
      IF (SMM.GE.0.) SM(1)=SMM
      DO 425  I=1,NL
 425  SM(I+1)=XSOL(I)
      DO 430 I=1,NL
 430  XSOL(I)=TEMP(I)
      TEMP(1)=TPP
      DO 440 I=1,NL
 440  TEMP(I+1)=XSOL(I)
 450  CONTINUE
```

```
      RETURN
 10   FORMAT(75A1)
 20   FORMAT(I5)
 30   FORMAT(3F10.2)
 600  CONTINUE
      IF (XMAX.LT.0.00) WRITE (6,730)
      IF (NLMAX.GT.99) WRITE (6,710)
 710  FORMAT(15X,' NO OF POINTS IN SOIL GAPA SET TOO LARGE')
 720  FORMAT(20X,' SOIL DEPTH IN DATA SET TOO LARGE ')
 730  FORMAT(20X,' SOIL DEPTH HAS NOT BEEN SPECIFIED PROPERLY')
      RETURN 1
      END
// EXEC LINKGO,REGION.GO=150K
//GO.SYSUDUMP DD SYSOUT=A
//GO.DATA5 DD *
```

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